Forecast of the track and intensity of the tropical cyclone AILA over the Bay of Bengal by the global spectral atmospheric model VARSHA

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The tropical cyclone 'AILA' formed over the Bay of Bengal and crossed the West Bengal coast in the afternoon of 25 May 2009. The track, surface pressure distribution, asymmetric wind, warm core, etc. and special features like rapid intensification near the coast and retention of intensity after landfall are examined in the forecast of model VARSHA. This model predicted the rapid intensification and sustained intensity after landfall indicating interaction with a cold core trough in the westerly. Comparison with observations by IMD and also the FNL analysis of NCEP, USA shows that VARSHA performed well in predicting the structure, motion and intensification of AILA.

Keywords: Atmospheric model, asymmetric wind, rapid intensification, tropical cyclone, westerly interaction.

ON 22 May 2009, a low pressure area formed over the southeast Bay of Bengal in the morning, at the leading edge of the advancing monsoon current. The formation of a vortex at the time of onset of the summer monsoon over India is a well-known phenomenon[1,2], though its formation is more common over the Arabian Sea. The low intensified into a depression after about 30 h and India Meteorological Department (IMD) fixed its location at 16.5°N and 88.0°E at 0600 UTC of 23 May 2009. Thereafter, IMD continued to fix its centre, initially from satellite imagery and then from observations of Doppler radar at Kolkata as the system came close to the coast, till it dissipated over the northern part of West Bengal after 0600 UTC of 26 May 2009. The system acquired the intensity of a deep depression (maximum wind exceeding 27 kt) at 0300 UTC of 24 May, a cyclonic storm (maximum wind exceeding 33 kt) at 1200 UTC of 24 May and severe cyclonic storm (maximum wind exceeding 47 kt) at 0600 UTC of 25 May, only 2–3 h before it crossed the coast near Diamond Harbour (close to 21.5°N, 88.0°E). The system was named 'AILA' as it attained the intensity of a cyclone. The location of the centre of the cyclone, central pressure and maximum wind as estimated by IMD[3] and also the values forecast by the global spectral atmospheric model VARSHA of the Flosolver Unit, National Aerospace Laboratories (NAL), Bangalore, are presented in Table 1.

The VARSHA model is a hydrostatic global atmospheric model that uses spectral technique for the horizontal representation of the model variables. This model is being used at the Flosolver Unit, NAL, to produce real-time medium range weather forecast everyday and then integrated up to 30 days to evaluate the possibility of predicting monthly mean features deterministically. The VARSHA model has its roots in the National Centre for Medium Range Weather Forecasting (NCMRWF) T-80 code that was parallelized by NAL in 1993 (ref. 4). The model code was subsequently re-engineered using FORTRAN 90 (ref. 5) and new radiation[6] and boundary layer parameterization modules added to replace the existing ones. The boundary layer parameterization of Rao and Narasimha[7] is based on the findings from the MONTBLEX and BLX83 experiments, that conventionally defined drag and heat transfer coefficients increase rapidly as wind speed falls. A new velocity scale determined by the heat flux rather than by the friction velocity, as in the classical turbulent boundary layer theory, along with novel definitions of drag and heat exchange coefficients are used in the new parameterization scheme. The model code is flexible in spectral truncation number and in the number of points in the transformation grid. At present the spectral truncation of the model is at 120 waves in triangular truncation and the transform grid has 512 points in the east-west and 256 points in the north-south (Table 2). The extra points in the transform grid not only help in controlling the aliasing of shorter waves, but also provide better representation of the physical processes due to higher resolution. The 0000 UTC FNL analysis of the National Centers for Environmental Prediction (NCEP), USA, was used to initiate the model run. In this study, we compare forecasts from this model with estimates of position and intensity by IMD. We also compute various parameters characteristic of the cyclone and try to correlate the variation in the intensity of the system with

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Table 1. Observed (India Meteorological Department (IMD)) and forecast parameters of the severe cyclonic storm AILA over the Bay of Bengal during 23–26 May 2009

Date (May 2009)	Time (UTC)	Grade	Centre IMD	Centre VARSHA	Central pressure (hPa) IMD	Central pressure (hPa) VARSHA	Maximum wind (kt) IMD	Maximum wind (kt) VARSHA
23	0600	D	16.5°N/88.0°E	16.2°N/88.6°E	998	996.8	25	35.8
	1200	D	16.5°N/88.0°E	16.9°N/89.3°E	994	995.5	25	39.8
	1800	D	17.0°N/88.5°E	18.3°N/90.0°E	996	992.9	25	41.6
24	0000	D	17.0°N/88.5°E	18.9°N/90.0°E	996	990.6	25	43.2
	0300	DD	18.0°N/88.5°E	–	992	–	30	–
	0600	DD	18.0°N/88.5°E	20.4°N/90.0°E	988	988.3	30	47.8
	0900	DD	18.0°N/88.5°E	–	986	–	35	–
	1200	CS	18.5°N/88.5°E	21.1°N/90.0°E	986	986.6	35	44.9
	1500	CS	19.0°N/88.5°E	–	986	–	35	–
	1800	CS	19.0°N/88.5°E	22.5°N/90.0°E	986	986.5	35	50.0
	2100	CS	20.0°N/88.0°E	–	984	–	40	–
25	0000	CS	20.0°N/88.0°E	23.2°N/89.3°E	980	984.9	40	49.6
	0300	CS	20.5°N/88.0°E	–	978	–	50	–
	0600	SCS	21.5°N/88.0°E	24.6°N/89.3°E	974	985.1	55	45.6
	0900	SCS	22.0°N/88.0°E	–	968	–	60	–
	1200	SCS	22.5°N/88.0°E	24.6°N/90.0°E	970	987.8	50	37.0
	1500	CS	23.0°N/88.0°E	–	978	–	45	–
	1800	CS	23.5°N/88.0°E	26.0°N/90.7°E	980	991.3	40	33.7
	2100	CS	24.0°N/88.0°E	–	981	–	35	–
26	0000	CS	25.0°N/88.0°E	27.4°N/90.7°E	982	992.4	30	28.6
	0300	DD	25.5°N/88.0°E	–	988	–	25	–
	0600	D	27.0°N/88.5°E	26.0°N/83.7°E	992	994.8	20	23.4
	0900	LOW	–	–	–	–	–	–

the environmental variations during the lifetime of the cyclone.

The cyclonic storm AILA showed some special features like rapid intensification close to the coast and retaining intensity at the level of a severe cyclonic storm for more than 12 h after landfall. This cyclone is the first storm in the last 20 years to cross the West Bengal coast in May. Under its influence very strong surface winds were experienced over the whole of southern West Bengal, leading to extensive uprooting of trees up to the state capital of Kolkata, about 80 km inland from the coast. The storm surge associated with the cyclone was about 2 m over the Sunderbans and about 3 m over adjoining Bangladesh. Since the astronomical tide at the time of landfall was between 4 and 5 m, the storm surge led to a total sea-level elevation exceeding 6 m and was the prime cause for loss of human lives in both India (about 100) and Bangladesh (about 175). Under the influence of AILA, rainfall was copious over the whole of West Bengal, Sikkim and parts of Nepal. Large amounts of rainfall were also recorded over Orissa and the whole of Northeast India.

Track of AILA

The severe cyclonic storm moved almost northwards from the day of its intensification as a depression to the day it dissipated as a low over the north of West Bengal. This is the usual climatological track of cyclones originating over the same area in the southeast Bay of Bengal during May. The observed track of the cyclone (Figure 1) shows a latitudinal displacement of 10.5° from 16.5°N to 27.0°N, almost along the 88.5°E meridian. Thus, the average speed of translation of the storm, during its lifetime as a depression or higher intensity system, was about 10 n mile/h. The track of AILA obtained from the location of the lowest mean sea level pressure (MSLP) value in the forecast of VARSHA model from the initial condition at 0000 UTC of 23 May 2009 is also plotted in Figure 1. It is seen that the forecast position at 0600 UTC is to the right (east) of the observed location and the forecast track is almost parallel to the observed track, being closer to 90.0°E rather than the 88.5°E meridian followed by the real storm. However, the direction of movement of the model storm was almost uniformly northward as in the observed and the average speed of translation was also close to that of the real storm.

The major sources of error in track prediction of a tropical cyclone by an atmospheric model are the representation of the environmental flow and the correct location of the cyclone in the initial condition. A tropical cyclone is embedded in the environment and is translated by the mean flow called the 'steering current' in the environment. Techniques to estimate this mean flow of the environment from the observed flow within a cyclone field were developed to isolate the steering flow and use the same for statistical or synoptic cyclone track prediction methods. Up to 80% of the variance of tropical cyclone motion can be explained by the large-scale

Table 2. Some characteristics of the VARSHA weather forecast model

Dynamics	
Spectral resolution	120 waves in triangular truncation
Transform grid	512 equally spaced points in the east-west 256 Gaussian grid points in the north-south
Vertical coordinates	18 sigma levels (0.995, 0.981, 0.96, 0.92, 0.856, 0.777, 0.688, 0.594, 0.497, 0.425, 0.375, 0.325, 0.275, 0.225, 0.175, 0.124, 0.074, 0.021)
Vertical differencing scheme	Arakawa vertical finite differencing scheme[13,14]
Time integration scheme	Leapfrog scheme
Integration time step	7.5 min
Physics	
Radiation	Lacis and Hansen short-wave[15] and Fels–Schwarzkopf's GFDL long-wave formulation[16].
Shallow convection	Tiedtke's formulation[17]
Deep convection	Kuo–Anthes scheme[18,19]
Grid scale condensation	Kessler[20]
PBL parameterization	New scheme based on the scaling arguments of Rao and Narasimha[7]
Land surface process	Three-layer soil model for soil temperature and bucket hydrology of Manabe[21] for soil moisture prediction
Air–sea interaction	Roughness length over sea computed by Charnock's[22] relation
Gravity wave drag parameterization	Lindzen and Pierrehumbert formulation[23,24]
Surface boundary data	
Orography	Consistent with the FNL data of NCEP
Sea surface temperature (SST)	Actual SST from the FNL analysis of NCEP for the first day and anomaly added to climatology for subsequent days
Soil moisture	Climatological
Deep soil temperature	Climatological
Albedo	Climatological
Surface roughness	Climatological
Cloud cover	Climatological
Snow cover	Climatological
Sea ice	Climatological
Computer resources	
Computer	Flosolver Mark 8 with Intel Xeon Quad core processors
Operating system	Red Hat Enterprise Linux
Computational performance	About 10 min computation time on four processors

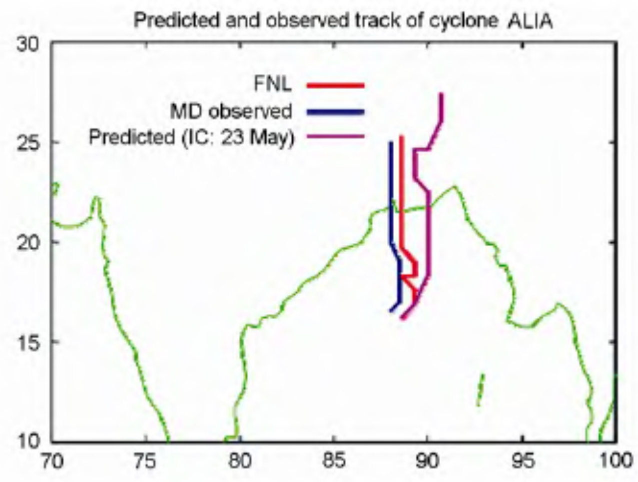

Figure 1. Predicted track of cyclonic storm AILA from initial condition of 0000 UTC of 23 May 2009.

environmental flow[8,9] and its estimation provides valuable support for track prediction. The major difficulties arise from removal of the cyclone circulation and in determining the appropriate level or layer mean. In a dynamic model the wind assimilated from observation is the resultant of both winds due to the cyclone as well as those due to the environment. Since observations are few from within the cyclone field and the component of the wind due to the cyclone is much higher than that due to environment, there is large error in the environmental component of the analysed wind field.

The error in the location of the cyclone in the initial condition of a forecast model is mainly due to the error in short-range prediction of the centre of the cyclone and lack of sufficient high-quality observations from within the cyclone field to correct the same. Also, when the centre of the cyclone is identified as the point of lowest pressure at the mean sea level, as in this case, the location of the centre can take only discrete values separated by the grid size of the model. The atmospheric fields within the cyclone area have large asymmetry for most of the variables and it is extremely difficult to separate the cyclone field from the total analysis and relocate it in a more realistic location[10]. The error in the initial position of the cyclone is carried throughout the forecast length and in the present case (Figure 1) appears to contribute significantly to the total error in the track forecast.

Mean sea-level pressure associated with AILA

The central pressure of a cyclone falls gradually as it intensifies from the initial vortex stage and the radius of the strongest pressure gradient contracts. According to IMD estimates, first from the cloud pictures and later from the Doppler radar observation as the cyclone approached the coast, the central pressure deepened by 30 hPa whereas the pressure drop (difference between the outer peripheral and central pressures) increased from 3 hPa at the depression stage at 0600 UTC of 23 May 2009 to 20 hPa at 0900 UTC of 25 May 2009 as the peripheral pressure changed from 1001 to 988 hPa during the transition of the storm from 16.5°N to 22.5°N (Table 1). In fact, this cyclone attained its maximum intensity 6 h after its landfall, in contrast to many other cyclones that dissipate quickly after landfall.

In the forecast of the VARSHA model, the cyclone was close to the West Bengal coast at 1800 UTC of 24 May 2009 and crossed the coast by 0000 UTC of 25 May 2009 (Figure 2), that is about 9 h ahead of the observed time of landfall. The lowest value of central pressure in the model predicted MSLP field fell from 986.5 to 984.9 hPa (Table 1) after landfall and remained almost the same for the next 6 h before the cyclone finally started filling up. The outer closed isobar had a value of 998 hPa during this 6 h of intensification. For a spectral model with transform grid resolution of 0.7 degrees of arc, the reproduction of a central pressure drop of more than 13 hPa is remarkable as the steepest pressure decease occurs within the radius of maximum pressure gradient which normally lies within 50 km from the centre of the cyclone. It is also encouraging to note that the model simulated the intensification of the cyclone after landfall – an unusual event for a land-falling cyclone.

The MSLP field due to an intense cyclonic system is almost symmetric around the centre, especially over the sea areas where no differential surface friction distorts the pressure distribution. This idealized field is superposed on the large-scale pressure field with seasonal gradient to get a theoretical estimate of the observed pressure distribution at mean sea level. An axis-symmetric mathematical function was developed[11] for the idealized MSLP distribution in the form:

$$p(r) = p_\alpha - \Delta p \exp\{-((b-1)/b)(r/a)^b\}, \quad (1)$$

where p_α is the ambient pressure far away from the cyclone centre, Δp the pressure deficit at the centre with respect to the ambient pressure (in hPa), b the real number related to the size of the storm and a the radial distance (in km) where the pressure gradient is maximum.

By comparison with several observed pressure distributions inside land-falling cyclones, the value 1.7 was found to be the most suitable for the parameter b for cyclones over the Bay of Bengal. The parameter a is related to the radius of maximum wind and is to be estimated from satellite or radar observations of the radius of the maximum wind that lies within the wall cloud region. For the model prediction, the radius of maximum wind

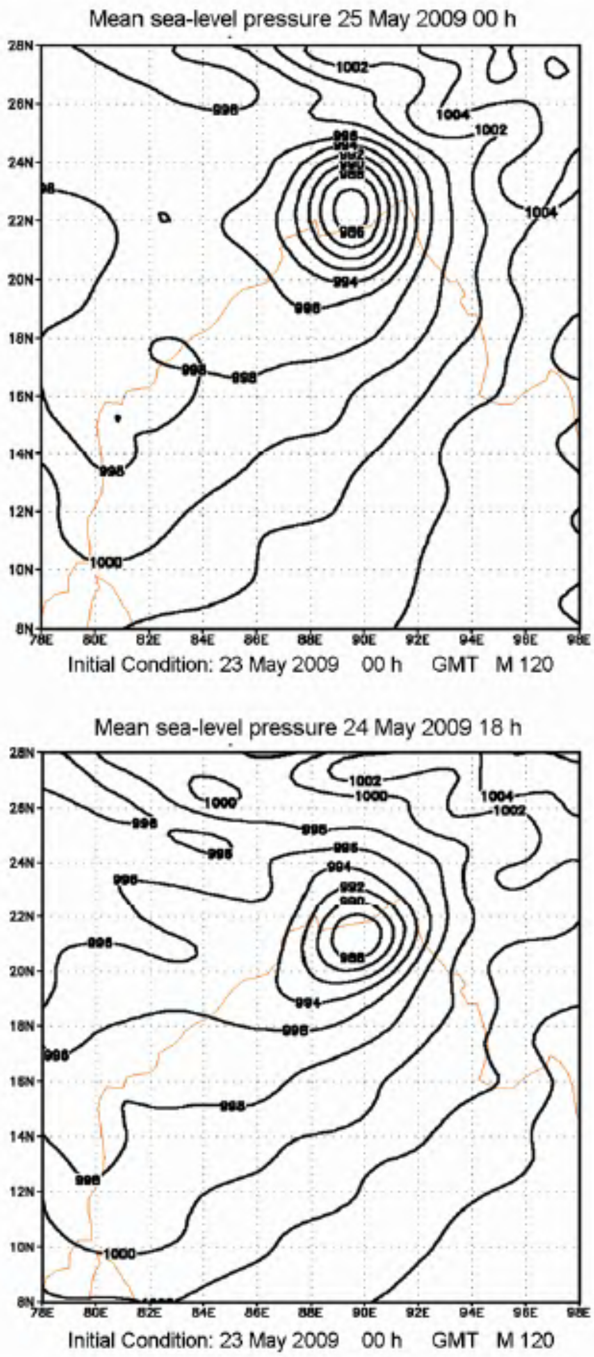

Figure 2. Mean sea-level pressure at 1800 UTC of 24 May 2009 (lower panel) and 0000 UTC of 25 May 2009 (upper panel) predicted from initial condition at 0000 UTC of 23 May 2009.

can be picked up from the forecast distribution of the wind around the centre of the cyclone.

As the cyclone retained its intensity for sometime after landfall and hourly observation of pressure was available from automatic weather stations (AWS) available at many locations in the path of the cyclone, an opportunity arose to verify the theoretical pressure profile presented earlier. Since a Doppler radar was available at Kolkata to determine the distance between the centre of the cyclone and the observation point, observations of AWS at Kolkata were compared with the surface pressure computed from eq. (1) and are presented in Figure 3. For computation of surface pressure from eq. (1), the peripheral pressure was taken as 990 hPa and the central pressure drop was taken as 20 hPa according to the estimates by IMD on the forenoon of 25 May 2009 (ref. 3). The radius of maximum wind was fixed at 126.2 km as predicted in the model forecast. Observations from AWS at Kolkata between 0300 and 1700 local time agree well with the surface pressure values computed from the theoretical pressure distribution profile and reconfirm that the assumed mathematical form in eq. (1) is reasonable for cyclones in the Bay of Bengal.

Surface wind associated with AILA

The surface wind associated with a tropical cyclone has typical characteristics of a calm centre surrounded by an almost circular, narrow ring of maximum wind known as the wall cloud region and then a large region where surface wind decreases with distance from the centre and merges with the environmental wind. The radius of maximum wind determines the size of the storm and its magnitude decreases as the storm intensifies. The strength of the maximum wind on the other hand determines the strength of the cyclone and its magnitude increases with

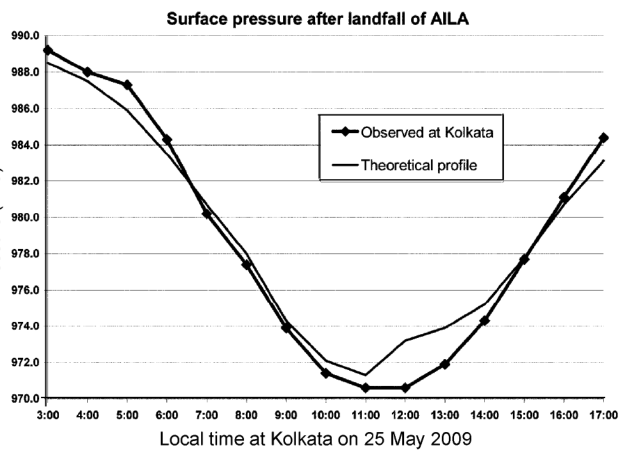

Figure 3. Surface pressure measured by the automatic weather station at Kolkata and predicted by the theoretical pressure profile of Basu and Ghosh[11]. According to the Doppler weather radar observation at Kolkata, the centre of cyclone AILA crossed Kolkata at a distance of 26.0 km at 11.00 am on 26 May 2009.

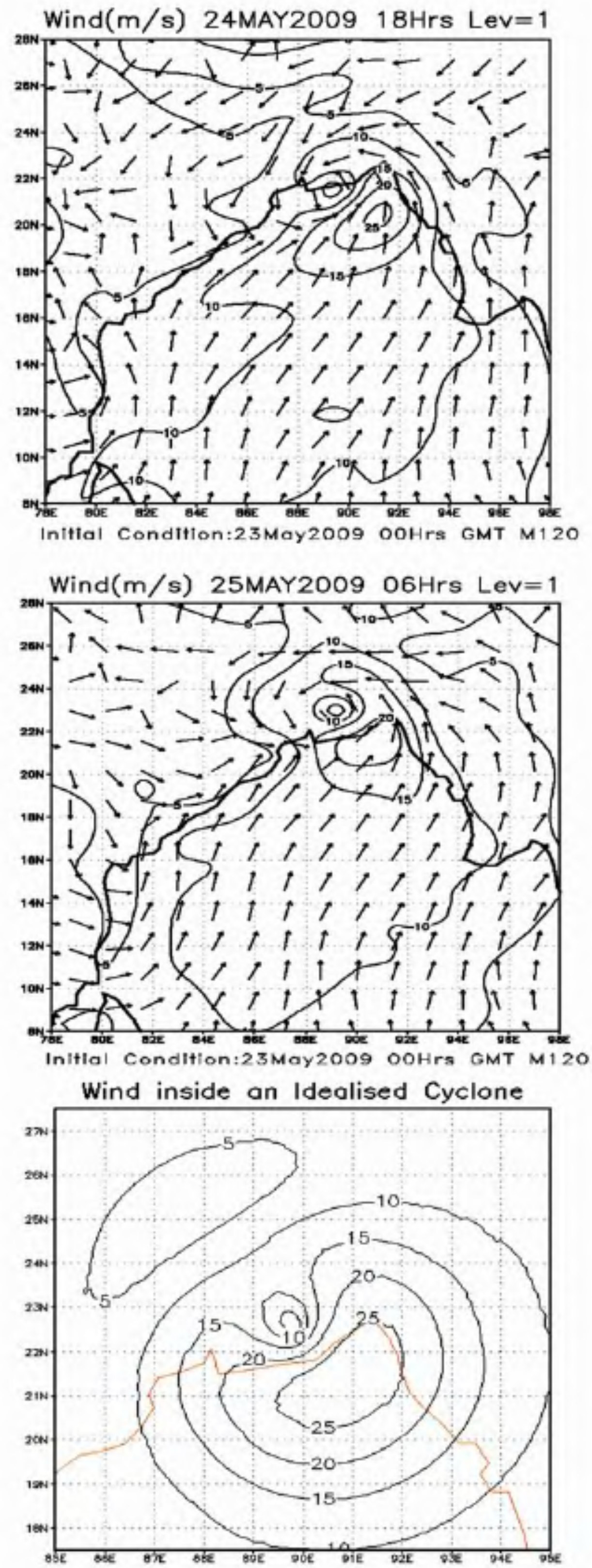

Figure 4. Surface wind at 1800 UTC of 24 May 2009 (upper panel) and 0600 UTC of 25 May 2009 (middle panel) predicted from initial condition of 0000 UTC of 23 May 2009. (Lower panel) Theoretically simulated wind field for cyclone conditions of 0600 UTC of 25 May 2009.

intensification. The maximum wind predicted by the VARSHA model within the field of AILA was 25.7 ms^{-1} on 1800 UTC of 24 May 2009 (Figure 4), whereas the smallest radius of maximum wind of 126.2 km was predicted about 12 h earlier.

The observed wind field within a cyclone has large asymmetry due to the motion of the storm, because of the difference in the value of the Coriolis parameter for different latitudes and also due to asymmetry in the environmental wind field. In the northern hemisphere the speed of translation of the cyclone adds up to the wind speed due to pressure gradient in the half of the cyclone that is to the right of the direction of motion, whereas it slows down the wind speed in the other half. In the northern hemisphere smaller magnitude of the Coriolis parameter at the southern latitudes supports stronger winds for the same pressure gradient leading to north-south asymmetry in the wind field in a symmetric pressure field around the centre of the cyclone. The environmental wind also adds up with the wind within the cyclone field and changes the orientation of the asymmetry in the observed wind field. The VARSHA model could predict the northward movement of the cyclone correctly, but the predicted track was to the right (east) of the observed one, separated by 1.5° of longitude. Part of this difference is due to the difference in the initial position of the cyclone. As a result of the displacement in the track of the cyclone, the model-predicted wind field also gets displaced to the east of the observed one. The environmental wind was south-southwesterly (about 210°), with strength nearly 10 ms^{-1}. This direction of the environmental wind rotated the east-west dipole of wind maximum and minimum, produced by the northward translation of the cyclone, by about 30° towards south.

The distribution of wind inside AILA, predicted by the VARSHA model, is shown in the upper and middle panels of Figure 4 for 1800 UTC of 24 May 2009 and 0600 UTC of 25 May 2009. The lower panel of Figure 4 shows the distribution of wind inside a cyclone having the same central pressure drop and radius of maximum wind as that in the model prediction for AILA at 0600 UTC of 25 May 2009, with a translation speed of 10 kt/h towards due north and embedded in an environmental wind of 10 ms^{-1} in the south-southwesterly (210°) direction. Comparison of the middle and lower panels shows good agreement between the VARSHA-predicted wind field and the simulation of surface wind using the quasi-equilibrium model for a cyclone in a coordinate system translating with the centre of the cyclone[12]. Both the strength and asymmetry in the wind field are simulated well by the diagnostic surface wind model.

Temperature distribution within AILA

At 0000 UTC of 24 May 2009, the longitude–height cross-section of the departure of virtual temperature from its environmental value at the periphery of the cyclone, at the centre of the cyclone shows a warm core extending from the surface above up to 16 km, with one maximum of more than 6°C between 5 and 6 km amsl and another maximum of more than 5°C between 9 and 12 km amsl. The heating is due to adiabatic compression of descending air in the eye of the cyclone and diabatic release of heat due to condensation of water vapour into liquid water close to the ground (~ 300 m msl) and subsequent freezing of liquid water into ice near the freezing level (~ 6 km). The latent heat released is carried upwards by

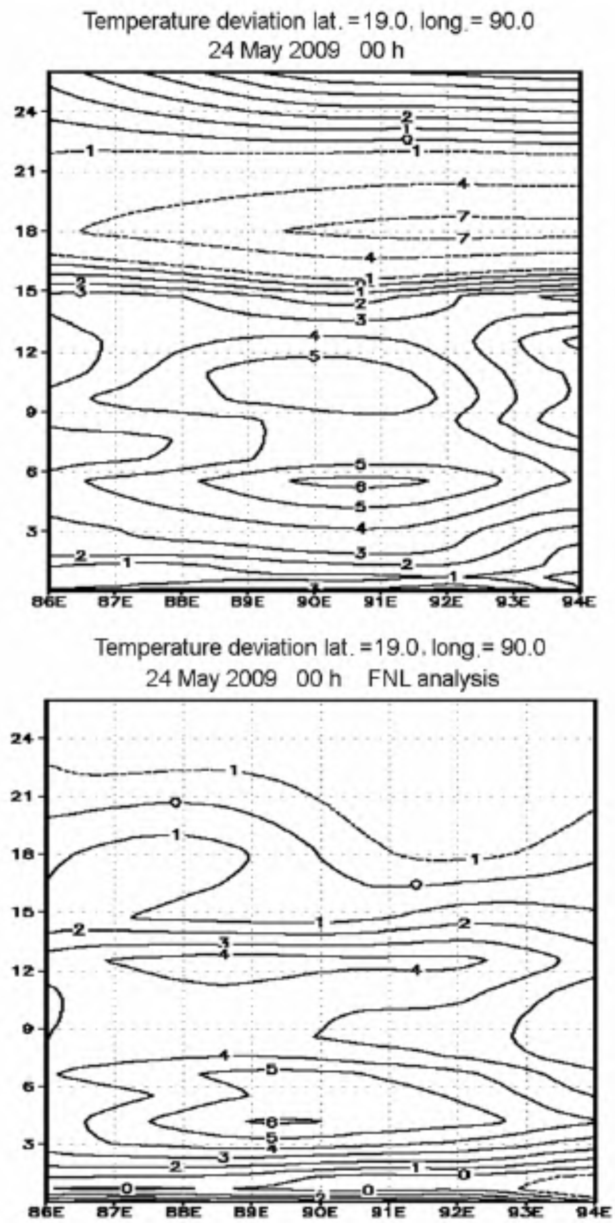

Figure 5. Longitude–height cross-section of departures of virtual temperature from the average between 86 and 94E through the centre of the cyclone. (Upper panel) Model forecast from initial condition of 0000 UTC of 23 May 2009. (Lower panel) Initial condition of 0000 UTC of 24 May 2009.

the vertical motion in convective clouds present within the wall cloud region surrounding the central eye. Above 16 km a cooler area appears above the central core of the cyclone as the dry warm air is carried upwards by inertia and cools adiabatically. This pool of cool air produces a thermodynamic high associated with mass divergence that compensates the mass convergence in the lower levels of the cyclone. In the case of AILA, this layer of cool air extended up to 22 km as seen in the forecast for 0000 UTC of 24 May 2009 (upper panel, Figure 5). Strongest cooling of magnitude exceeding 7°C was observed at 18 km, close to the tropopause.

In the FNL analysis of NCEP (lower panel, Figure 5), the warming in the middle troposphere was of similar magnitude as in the forecast but is located about a kilometre lower than in the forecast. On the other hand, the upper tropospheric warm core was located higher than in the forecast and was weaker in magnitude. The cooling in the stratosphere was much smaller in magnitude and located higher up than in the forecast. A comparison of the heating/cooling inside the cyclone, with respect to the longitudinal average, shows a pattern similar to that in the NCEP analysis, except for the locations of the maximum and minimum. The magnitudes of heating cores in the forecast were comparable to those in the analysis, but the magnitude of cooling has been overestimated in the forecast, with a strong core of cooling close to the tropopause.

Rainfall associated with AILA

The highest amount of rainfall recorded in association with the cyclone AILA was 270 mm on 27 May 2009 at Darjeeling, West Bengal, located at a height of 2128 m in the lower part of the eastern Himalayas. Very heavy rainfall in excess of 125 mm was recorded at many stations in West Bengal, Orissa and Meghalaya, whereas heavy rainfall in excess of 650 mm was recorded in Bangladesh and Nepal. Most of the heavy spells were associated with the wall cloud region surrounding the eye of the cyclone but some, especially those over Orissa on 25 May 2009, were due to the cloud bands spiralling into the centre of the cyclone with vertical velocity strengthened by the juxtaposition of the divergence area of a westerly trough. The model forecast precipitation ending on 25 May 2009 indicates heavy rainfall over the south of Bangladesh, about 5° to the east of the observed rainfall area over north Orissa. The very heavy (13–20 cm) and extremely heavy (> 20 cm) spells have been underestimated in the model prediction and the spatial distribution was more to the south over the sea than to the north and east as in the observed rainfall. On 26 May 2009 the model forecast precipitation belt again shifted to the east of the observed centre of the cyclone, but on this day the observed rainfall also extended to the east due to the southerly flow induced to the east of the cyclone centre. On 27 May 2009, the model-predicted precipitation was confined to the north of Assam and Arunachal Pradesh, whereas observed rainfall was over the sub-Himalayan West Bengal and adjoining areas. On all days precipitation amounts exceeding 13.0 cm (very heavy and above) were underestimated in the model forecast. However, it should be kept

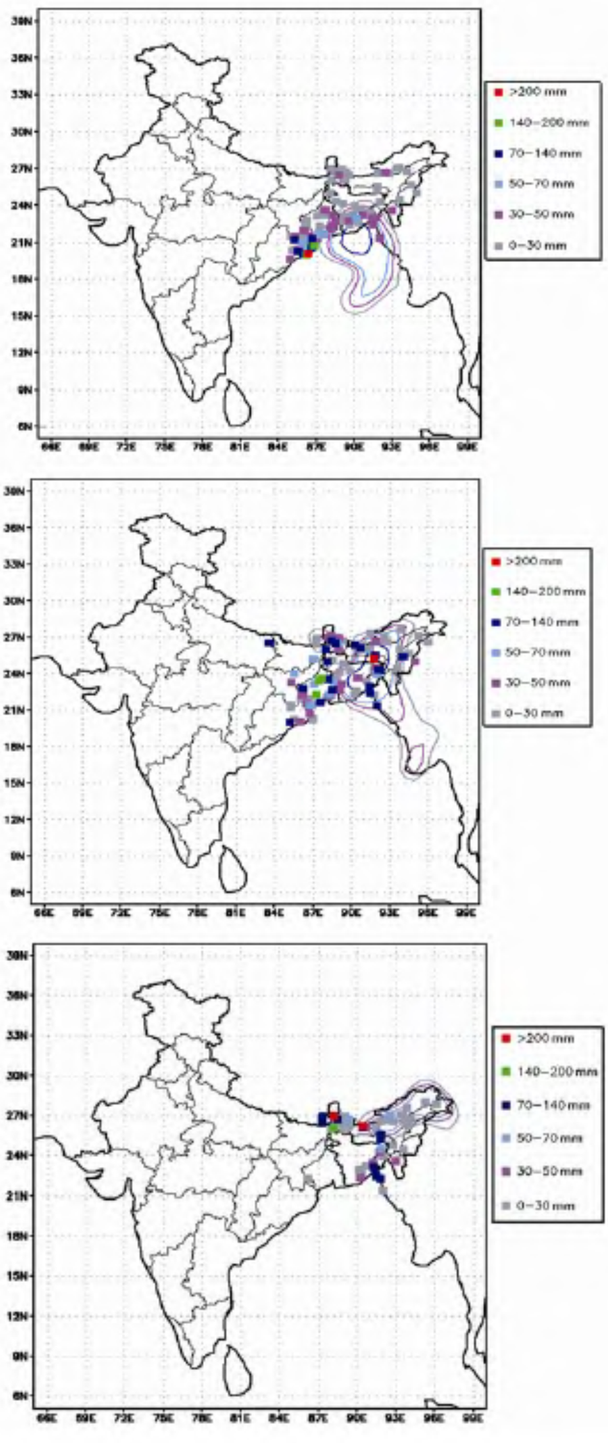

Figure 6. Observed (shaded) and VARSHA model-predicted rainfall for 25 May (upper panel), 26 May (middle panel) and 27 May 2009 (lower panel).

in mind that model rainfall is an average over an area surrounding the model grid point. For the VARSHA model the grid box is almost a square with sides approximately 80 km. Individual rain gauges represent a smaller area not exceeding a circle of radius 30 km around the station. Since rainfall is a highly variable field with recorded variation exceeding 50 cm in a day within a distance of less than 30 km, the model will not be able to reproduce magnitudes of very heavy rainfall till the grid box size becomes comparable to the area of observed very heavy rainfalls. In the tropics, such spells are associated with thunder storms and the model resolution should be fine enough to capture these systems explicitly for any realistic prediction of precipitation. The observed and model predicted rainfall for 25–27 May 2009 is presented in Figure 6.

Genesis and intensification of the cyclone as seen in the model forecast

The cyclonic vortex at the leading edge of the monsoon current intensified into a depression at 0600 UTC of 23 May 2009 when the upper level divergence strengthened and the vertical velocity increased to 1.0 Pa/s close to the centre of the system. This was the time when the convection organized within the low pressure area and a warm layer appeared close to the centre extending up to the middle troposphere. The next significant increase in the magnitude of the vertical velocity was at 1800 UTC of 24 May 2009, when the strength of the vertical motion field almost doubled in magnitude and this persisted till 0000 UTC of 26 May 2009, after which it collapsed abruptly. During the life period of the AILA a mid-latitude trough extending from an extra-tropical cyclone located close to 65°N was approaching the system and came close to it to interact and combine into one intense field of vertical velocity. The longitude–height cross-section of vertical velocity presented in Figure 7, shows that the vertical velocity fields of two separate systems merged after 1200 UTC of 26 May 2009 to intensify the cyclone into a severe one. At this time the cyclone was close to the coast and normally enhanced convergence in the lower troposphere due to surface friction coupled with loss of moisture source over the sea would have reduced the intensity of the storm. The interaction of the cold-core trough (Figure 8) extending from a mid-latitude cyclone located near 67°N and 87°E at 0600 UTC of 24 May 2009, not only intensified the tropical system into a severe cyclone, but also maintained its intensity for a day after landfall. By this time the tropical vortex had moved away from the divergence area of the westerly system and the decreased vertical velocity was not enough to pull moisture from the Bay of Bengal. This cutting-off of the moisture source killed the convection and low-level convergence filled up the system within hours. The longitude–height cross-section of divergence close to the centre of the cyclone centre presented in Figure 9 reflects the observed variation in the intensity of the cyclone.

The interaction of a tropical low-pressure system with a trough in the westerly is not uncommon and during the southwest monsoon season this is the mechanism that leads to the recurvature of a west/west-northwest moving depression towards north and then towards east. However, such interactions are common only to the west of the 75°E meridian and interaction of mid-latitude cold-core trough with a tropical cyclone is a rare phenomenon over

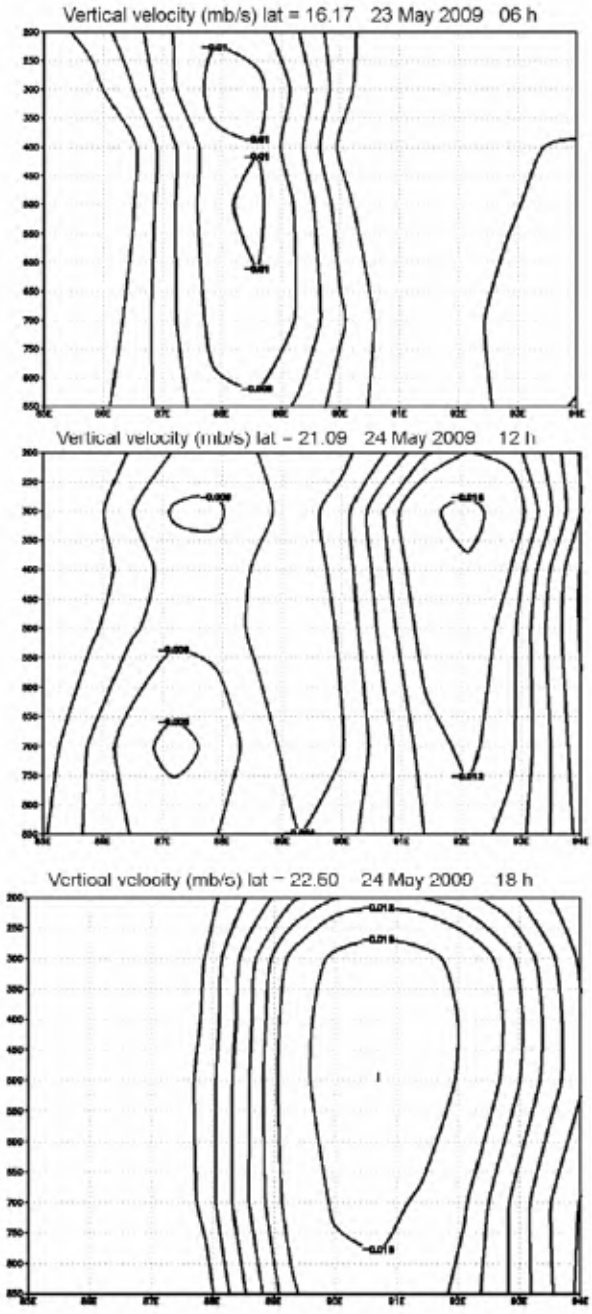

Figure 7. Longitude–height cross-section of vertical velocity close to the centre of AILA at 0600 UTC of 23 May (upper panel), 1200 UTC of 24 May (middle panel) and 1800 UTC of 24 May 2009 (lower panel).

the Indian sub-continent. The dynamic VARSHA model has reproduced this rare event with reasonable accuracy.

Discussion and conclusion

From the above description of the observed features of the cyclone AILA and analysis of the real-time predictions from VARSHA atmospheric model at NAL, the following conclusions can be arrived at:

1. The northward movement of the cyclone AILA was well reproduced in the VARSHA model forecast and the track of the cyclone was parallel to the observed track with a shift of about 1.5° to the east.
2. The central pressure predicted by the model fell to 984.9 hPa on 0000 UTC of 25 May 2009 and remained practically the same for the next 6 h, whereas IMD estimated central pressure fell to 968 hPa at 0900 UTC on the same date. The observed peripheral pressure fell from 1001 to 988 hPa, whereas it remained almost the same at 998 hPa in the model forecast. The estimated central pressure drop was 20 hPa, whereas the model reproduced a pressure drop of 13.1 hPa.
3. The magnitude of maximum wind within the cyclone field was predicted by the model as 25.7 ms^{-1} on 1800 UTC of 24 May 2009, whereas that estimated by IMD from satellite cloud picture was 60 kt (~30 ms^{-1}) at 0900 UTC of 25 May 2009. Thus the model reproduced the maximum wind reasonably well, but the time of peak intensity was about 15 h earlier than observed.
4. The smallest radius of maximum wind was predicted by the model as 126.2 km at 0600 UTC of 24 May 2009 that is 12 h before the onset of strongest maximum wind.

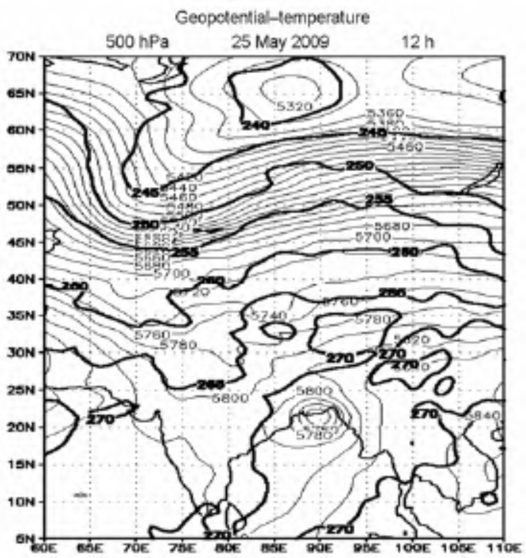

Figure 8. The contour and temperature field forecast by VARSHA at 1200 UTC of 24 May 2009 at 500 hPa level. The interaction of the cold-core trough led to a fall of contour height at the centre of the cyclone by 20 gpm at 500 hPa within the next 6 h.

5. The model-produced heating inside the cyclone was up to about 16 km with magnitude exceeding 6°C in the middle levels. Aloft there is a region of cooling with magnitude exceeding 7°C near the tropopause.

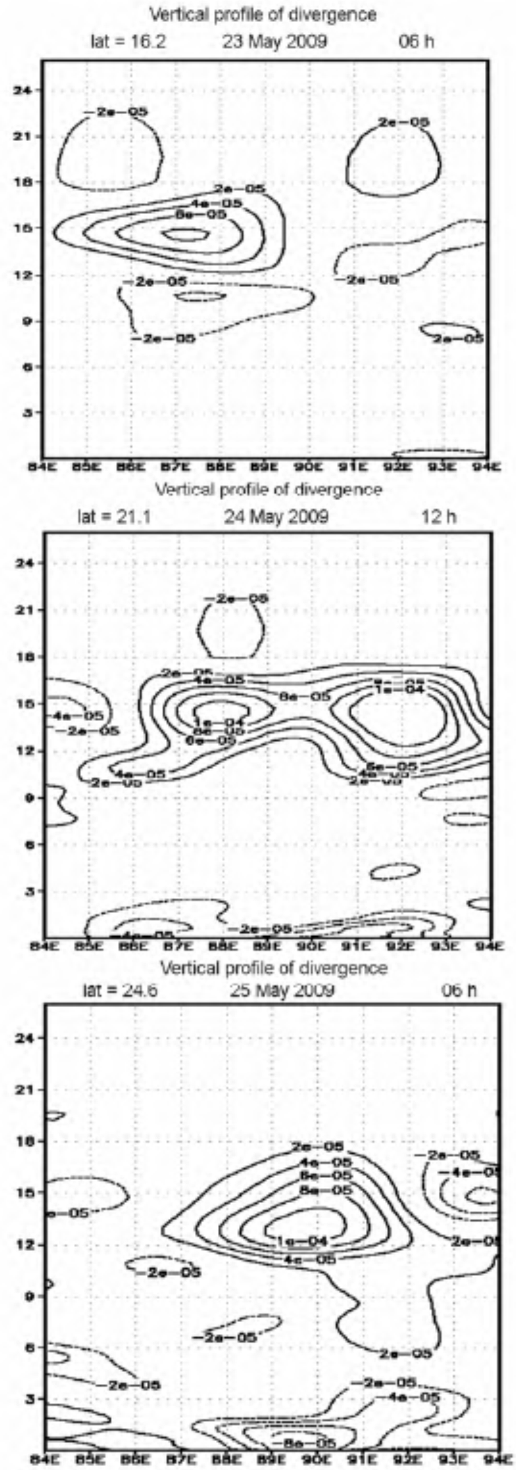

Figure 9. Longitude–height cross-section of divergence for 0600 UTC of 23 May (upper panel), 1200 UTC of 24 May (middle panel) and 0600 UTC of 25 May 2009 (lower panel). At these times the tropical system intensified from a low to a depression, deep depression to cyclonic storm and from cyclonic storm to severe cyclonic storm respectively.

6. A comparison of rainfall amounts predicted by the VARSHA model with the observed ones recorded by the meteorological agencies of India, Bangladesh and Nepal, showed that the location of predicted rainfall was to the east of that observed, as expected from the eastward displacement of the predicted track of the cyclone. The model-predicted grid-box average rainfall was lower in magnitude than the point rainfall recorded by the rain gauges.
7. The longitude–height cross-sections of vertical velocity through the centre of the cyclonic system showed a large increase in magnitude on 23 May 2009 at 0600 UTC when the system intensified into a depression for the first time. The magnitude of vertical velocity was the largest on 25 May 2009 at 0000 UTC when the upward motion field due to a trough in the geopotential field at the trailing edge of an extra-tropical system combined with that of the tropical cyclone. It remained almost the same for the next 24 h before it abruptly collapsed within 6 h by 0600 UTC of 26 May 2009.

From the above it can be concluded that the VARSHA model at spectral resolution of 120 waves in triangular truncation and with a transform grid resolution of about 0.7° of arc could reproduce the track of the cyclone reasonably well. The structure and other characteristics of the cyclone like central pressure drop, asymmetry in the wind field, cooling in the troposphere close to the centre, rainfall, etc. are also well reproduced by the model forecast. The special features of the cyclone AILA like intensification close to and after crossing the coast and retention of its intensity for a long time after crossing the coast were also simulated by the model.

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Intrinsic and scattering attenuation in Chedrang Fault and its vicinity – the rupture area of Great Assam earthquake of 12 June 1897 ($M = 8.7$)

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The attenuation of seismic waves is one of the basic physical parameters used in seismological studies, which is closely related to the seismicity and tectonic activity of a particular area. In the present study, attenuation properties of the crust beneath the Chedrang Fault and its vicinity, the rupture area of the great Assam earthquake of 12 June 1897 ($M = 8.7$) are studied using waveforms recorded by a local seismic network composed of five stations. In total 20 local earthquakes have been analysed to estimate (i) coda wave attenuation quality factor (Q_c) applying single scattering model, (ii) total attenuation quality factor (Q_d) from direct S-wave applying spectral ratio method and (iii) intrinsic and scattering attenuation quality factors (Q_i and Q_s) following the Wennerberg's approach. Coda Q (Q_c) values are obtained using different coda window lengths (20, 30 and 40 s) for frequency bands centred at 1, 1.5, 2, 3, 4, 6, 8, 12, 16 and 18 Hz. This study indicates that Q_c increases with increasing lapse time and that Q_c is frequency dependent following the attenuation–frequency relation $Q_{c(20)} = 36.29 \pm 1.18f^{1.45 \pm 0.09}$, $Q_{c(30)} = 69.92 \pm 1.11f^{1.23 \pm 0.06}$ and $Q_{c(40)} = 117.08 \pm 1.08f^{1.07 \pm 0.05}$ for 20, 30 and 40 s respectively. This behaviour is usually correlated to the presence of heterogeneity in the crust and to the degree of tectonic complexity underneath the study area. The Q_c^{-1} values for this area follow a substantially similar trend of Q_c^{-1} decay with frequency as the other tectonically active regions of the world.

Finally, from the separation of Q_s and Q_i values, it is observed that the study area can be characterized by a low scattering attenuation (small scattering Q inverse, Q_s^{-1}) and by a relatively high intrinsic attenuation (high intrinsic Q inverse, Q_i^{-1}).

Keywords: Chedrang Fault, coda waves, frequency dependence, intrinsic attenuation seismic waves, quality factor.

THE Chedrang Fault and its vicinity bounded by lat. 25°–26.4°N and long. 90°–91.8°E belongs to the western part of Shillong Plateau. It covers much of the maximum intensity (XII) zone of the great Assam earthquake of 12 June 1897 (ref. 1). This earthquake is a prominent among the great earthquakes of the world because of the large area over which it caused damage, liquefaction and landslides[2]. The earthquake almost totally destroyed settlements and small towns on the western part of the plateau and caused heavy damage in the surrounding areas mainly due to the extensive liquefaction to the ground. A relatively high level of microearthquake activity is still observed in the region[3–6].

Earthquake damage is primarily caused by seismic waves and shaking is heavily influenced by the manner in which seismic waves propagate through complex geological structures[7]. When seismic waves propagate through the earth, the wave amplitude decays with travel distance defining attenuation characteristics of the media. The knowledge of seismic wave attenuation in a given region is necessary to obtain information on earthquake source parameter and also for the assessment of seismic hazard in a region[8–10]. The attenuation of high frequency seismic wave is expressed as an inverse of quality factor Q (ref. 11), i.e. Q^{-1} and it is a useful tool to study the attenuation properties of the media towards understanding the physical laws related to seismic wave propagation. Seismic wave attenuation described by quality factor Q is a complex mechanism. The main contributing factors towards Q are intrinsic attenuation (Q_i^{-1}) due to medium anelasticity and scattering attenuation (Q_s^{-1}) associated with inhomogeneities. Quantitative contribution of these factors is important for correct geological and tectonic interpretation[7,12–21].

The main objective of this study is to obtain the attenuation properties of the crust beneath the Chedrang Valley area of the active Shillong Plateau by using local earthquakes and to ascertain the estimates of the quality factor of direct S-wave (Q_d) and coda wave (Q_c). Finally, the intrinsic attenuation (Q_i^{-1}) and scattering attenuation (Q_s^{-1}) are separated.

The coda wave attenuation quality factor, Q_c, is estimated applying single scattering model of Aki[22], modified by Aki and Chouet[23] and Sato[24]. In this method, coda

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